CLAIMS

WHAT IS CLAIMED IS:

1. A method for use in combination with a crystal growing apparatus for growing a monocrystalline ingot according to the Czochralski process, said crystal growing apparatus having a heated crucible containing a semiconductor melt from which the ingot is grown, said ingot being grown on a seed crystal pulled from the melt, said method comprising the steps of:

defining a temperature model representative of variations in the temperature of the melt in response to variations in power supplied to a heater for heating the melt;

pulling the ingot from the melt at a target rate, said target rate substantially following a predetermined velocity profile;

generating a signal representative of an error between a target diameter of the ingot and a measured diameter of the ingot;

performing proportional-integral-derivative (PID) control on the error signal and generating a temperature set point as a function thereof, said temperature set point representing a target temperature of the melt;

determining a power set point for the power supplied to the heater from the temperature model as a function of the temperature set point generated by the PID control; and

adjusting the power supplied to the heater according to the power set point thereby changing the temperature of the melt to control the diameter of the ingot.

Sub B1

2. The method of claim 1 wherein the step of adjusting the power includes applying a pulse of power to the heater, said power pulse having a predetermined duration and an amplitude greater than a steady state value corresponding directly to the temperature set point.

3. The method of claim 2 wherein the step of determining the power set point includes calculating power output by the following:

Sub E1

$$P_1 = P_0 + G * \left[k * \sum_{n=0}^{i} T_n - (k-1) * \sum_{n=0}^{i} T_{n-m} \right]$$

where P_1 is current power, P_0 is initial power, G is a conversion from temperature units to kW, k is the amplitude of the power pulse, T_n is the temperature set point at time t = n, T_{n-m} is the temperature set point at time t = n-m and m represents the duration of the power pulse.

4. The method of claim 1 wherein the step of determining the power set point from the temperature model includes defining an input to the temperature model, said input to the temperature model including a pulse portion followed by a steady state portion.

5. The method of claim 4 wherein the pulse portion of the input to the temperature model has an amplitude greater than a steady state value corresponding directly to the temperature set point.

6. The method of claim 4 wherein the pulse portion of the input to the temperature model has a duration defined by:

$$t = -\tau * \ln(1 - 1/k)$$

where τ is a time constant of an exponential function defining the temperature model and k represents the amplitude of the pulse portion of the input to the temperature model.

7. The method of claim 1 wherein the step of defining the temperature model includes defining a delay period, gain and first-order lag function response.

Sub E1

8. The method of claim 7 wherein the step of defining the temperature model includes defining the first-order lag function response by an exponential function of time as follows:

$$f(t) = k * (1 - \exp(-(t - t_d)/\tau))$$

where t_d is the delay period occurring prior to the first-order lag function response, τ is a time constant of the function and k represents the amplitude of a power input to the temperature model.

Sub C2

9. The method of claim 1 further comprising the step of varying the rate at which the ingot is pulled from the melt to control diameter of the ingot, said step of varying the pull rate occurring during growth of a first portion of the ingot and said step of pulling the ingot at the target rate substantially following the predetermined velocity profile occurring during growth of a second portion of the ingot.

10. The method of claim 1 wherein the step of defining the temperature model includes measuring changes in the temperature of the melt in response to changes in the power supplied to the heater.

11. An apparatus for use in combination with a crystal growing apparatus for growing a monocrystalline ingot according to the Czochralski process, said crystal growing apparatus having a heated crucible containing a semiconductor melt from which the ingot is grown, said ingot being grown on a seed crystal pulled from the melt, said apparatus comprising:

a predetermined velocity profile, said ingot being pulled from the melt at a target rate substantially following the velocity profile;

a proportional-integral-derivative (PID) control generating a temperature set point as a function of an error between a target diameter of the ingot and a measured diameter of the ingot, said temperature set point representing a target temperature of the melt;

a temperature model representative of variations in the temperature of the melt in response to variations in power supplied to a heater for heating the melt, said temperature model determining a power set point for the power supplied to the heater as a function of the temperature set point generated by the PID control;

a heater for heating the melt; and

a power supply responsive to the power set point for adjusting the power applied to the heater thereby changing the temperature of the melt to control the diameter of the ingot.

12. The apparatus of claim 11 wherein the power set point defines a pulse of power to the heater, said power pulse having a predetermined duration and an amplitude greater than a steady state value corresponding directly to the temperature set point.

13. The apparatus of claim 12 wherein the power output defined by the power set point is calculated by the following:

$$P_1 = P_0 + G * \left[k * \sum_{n=0}^{i} T_n - (k-1) * \sum_{n=0}^{i} T_{n-m} \right]$$

where P_1 is current power, P_0 is initial power, G is a conversion from temperature units to kW, k is the amplitude of the power pulse, T_n is the temperature set point at time t = n, T_{n-m} is the temperature set point at time t = n-m and m represents the duration of the power pulse.

14. The apparatus of claim 11 wherein the power set point is defined as a function of an input to the temperature model, said input to the temperature model including a pulse portion followed by a steady state portion.

15. The apparatus of claim 14 wherein the pulse portion of the input to the temperature model has an amplitude greater than a steady state value corresponding directly to the temperature set point.

16. The apparatus of claim 14 wherein the pulse portion of the input to the temperature model has a duration defined by:

$$t = -\tau * \ln(1 - 1/k)$$

where τ is a time constant of an exponential function defining the temperature model and k represents the amplitude of the pulse portion of the input to the temperature model.

17. The apparatus of claim 11 wherein the temperature model includes a delay period, gain and first-order lag function response.

18. The apparatus of claim 17 wherein the first-order lag function response of the temperature model is defined by an exponential function of time as follows:

$$f(t) = k * (1 - \exp(-(t - t_d)/\tau))$$

where t_d is the delay period occurring prior to the first-order lag function response, τ is a time constant of the function and k represents the amplitude of a power input to the temperature model.